Acoustic Inversion and 3-D Studies Employing Acoustic Vector Sensors in Shallow Water

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LONG-TERM GOALS

The goals of this research included the study of the effects of three-dimensional (3-D) environmental variability on the flow of energy in the complex intensity field, and the development of algorithms for environmental assessment based on measurements of the acoustic vector field. In the former case, the fully 3-D forward problem was modeled in order to gain a deeper understanding of the impact of shallow water features, such as solitons, on the propagation of acoustic energy. In the latter, inversion routines based on meta-heuristic approaches (e.g., simulated annealing) and more sophisticated models that directly incorporate the vector field into adjoint type methods were investigated to determine the general improvements in environmental assessment with the addition of information on the complex acoustic vector field.

OBJECTIVES

The overall objective of this work was to study the three-dimensional response of the acoustic vector field in the presence of environmental variability and noise, and the analysis of acoustic inversion techniques for environmental properties using meta-heuristic approaches and properties of the complex intensity field.

APPROACH

For the 3-D propagation portion of this work, a previously developed technique for computing the acoustic vector field from a PE model,[1,2,7] was expanded to generate solutions in 3-D environments using a Cartesian coordinate system.[8] The model was then employed to produce vector field data in a 3-D shallow water environment which incorporated perturbations due to shallow water non-linear

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14. ABSTRACT
The goals of this research included the study of the effects of three-dimensional (3-D) environmental variability on the flow of energy in the complex intensity field, and the development of algorithms for environmental assessment based on measurements of the acoustic vector field. In the former case, the fully 3-D forward problem was modeled in order to gain a deeper understanding of the impact of shallow water features, such as solitons, on the propagation of acoustic energy. In the latter, inversion routines based on meta-heuristic approaches (e.g., simulated annealing) and more sophisticated models that directly incorporate the vector field into adjoint type methods were investigated to determine the general improvements in environmental assessment with the addition of information on the complex acoustic vector field.

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internal wave structures.[9] The numerical data was then compared with analytical predictions based on a single scattering model developed by Prof. John Colosi (NPS).[3]

For part of the inversion studies, a new inversion method to estimate the geoacoustic properties of the sea floor using the specific acoustic impedance was investigated by Steven Crocker at the NUWCDIVNPT. This was based on the use of a forward model that requires relatively little information about the acoustic source. A numerical method based on the differential evolution (DE) algorithm was then employed to perform the inversions.[10]

In addition, environmental data from the MREA/BP'07 experiment[4] was utilized to create synthetic environments. Pressure data was collected during the experiment and a team led by Prof. Jean-Pierre Hermand (ULB) investigated various inversion techniques.[5] The 2-D version of the previously referenced PE model was then employed to generate predictions of the vector field in the presence of various environmental perturbations (e.g., turbulence, rough boundaries, etc). The inversion techniques were then expanded to incorporate vector field data, and sensitivity analyses were performed.

WORK COMPLETED

The 2-D Monterey-Miami PE (MMPE) model, which was updated several years ago to include computation of the acoustic particle velocity field, was upgraded for this work to compute the full 3-D propagation in Cartesian coordinates. In addition, an analytical prescription of a 3-D non-linear internal wave (NLIW) perturbation was incorporated. This perturbation assumed a uniform distribution along the NLIW front. The orientation of the wave front relative to the acoustic source/central propagation axis could be adjusted as an input parameter. Finally, multiple NLIW fronts could also be incorporated with a specific separation between each front.

The model was run for varying NLIW front angles assuming a mid-column source depth transmitting at 150 Hz. These solutions were decomposed into normal mode amplitudes using standard techniques. Comparisons were then made with predictions from the single-scattering model for varying NLIW orientations, multiple NLIWs, and mode coupling resonance behavior based on NLIW width. The primary measure used for comparisons was the ratio of modal energies (RME), which is a measure of energy coupled into or out of a particular mode.

For the inversion work performed by Steve Crocker, a method was developed in which the forward model (a wavenumber integration code) requires relatively little information about the acoustic source (location known and compact with respect to wavelength). A numerical method based on the differential evolution (DE) algorithm was employed. Factors contributing to this decision included the implementation simplicity, parallel execution and demonstrated robust numerical performance of the DE algorithm. Software to perform the inversion was developed and deployed on a small cluster of parallel processors, with validations for two canonical cases completed.

For the inversion work performed with Prof. Jean-Pierre Hermand, the 2-D MMPE model was employed. Environmental input data was based on a combination of the MREA/BP'07 experimental observations, and numerical perturbations including water column turbulence structure as well as rough bottom and sub-bottom boundaries. The analysis of this numerical vector field data is on-going, and the work completed to date will be reported separately by Prof. Jean-Pierre Hermand (ULB).

RESULTS

3-D Propagation Studies:

For propagation through a single NLIW, we showed that the single-scattering model predicts mode coupling levels consistent with the 3-D MMPE. The analysis showed that the single-scattering model produced RME fields with striation patterns of comparable size, shape, and magnitude to the 3-D MMPE. However, there were oscillations in the striation patterns computed using the 3-D MMPE model that were not predicted by the single-scattering model. This was most likely due to phase effects caused by the horizontal refraction of the modes. The single-scattering model was fundamentally a 2-D model, so such effects would not be predicted. Future work will attempt to incorporate these effects into the analytical predictions.

Figure 1 shows a comparison between the single-scattering predictions and the 3-D MMPE results for mode 5 at 150 Hz when the angle of NLIW front was perpendicular to the central axis of propagation (i.e., the direction of the NLIW directional vector was parallel to the central propagation axis). Correlation between the two predictions at 5 km was 99.9%.

Figure 2 shows a comparison between the single-scattering predictions and the 3-D MMPE results for mode 1 at 150 Hz when the direction of the NLIW directional vector was at 50 deg relative to the central propagation axis. Correlation between the two predictions at 5 km was 98.9%. Table 1 provides the correlation values between the two predictions at 5 km for modes 1, 2, 4, and 5 for NLIW directional vectors ranging from 0 to 80 deg.

Similar analysis was performed after incorporating a packet of multiple (3) NLIWs into the perturbation. The packet is composed of three NLIWs, each 100 m in width and separated by 500 m. The vertical displacement of the individual NLIWs from the first to the third is 10 m, 9 m, and 8 m, respectively. For the single-scattering model, all of the effects of the NLIW packet are summed and applied at the leading edge of the packet. In contrast, the 3-D MMPE model places the NLIW perturbations at their prescribed physical locations. To identify this point, two lines have been superimposed onto the RME field of the single-scattering solution to identify the beginning and end of the NLIW packet.

Figure 3 shows a comparison between the single-scattering predictions and the 3-D MMPE results for mode 5 at 150 Hz when the direction of the NLIW packet directional vector was parallel to the central propagation axis. Correlation between the two predictions at 5 km was 72.1%.

Figure 4 shows a comparison between the single-scattering predictions and the 3-D MMPE results for mode 1 at 150 Hz when the direction of the NLIW packet directional vector was at 50 deg relative to the central propagation axis. Correlation between the two predictions at 5 km was 66.8%. Table 2 provides the correlation values between the two predictions at 5 km for modes 1, 2, 4, and 5 for NLIW packet directional vectors ranging from 0 to 80 deg.

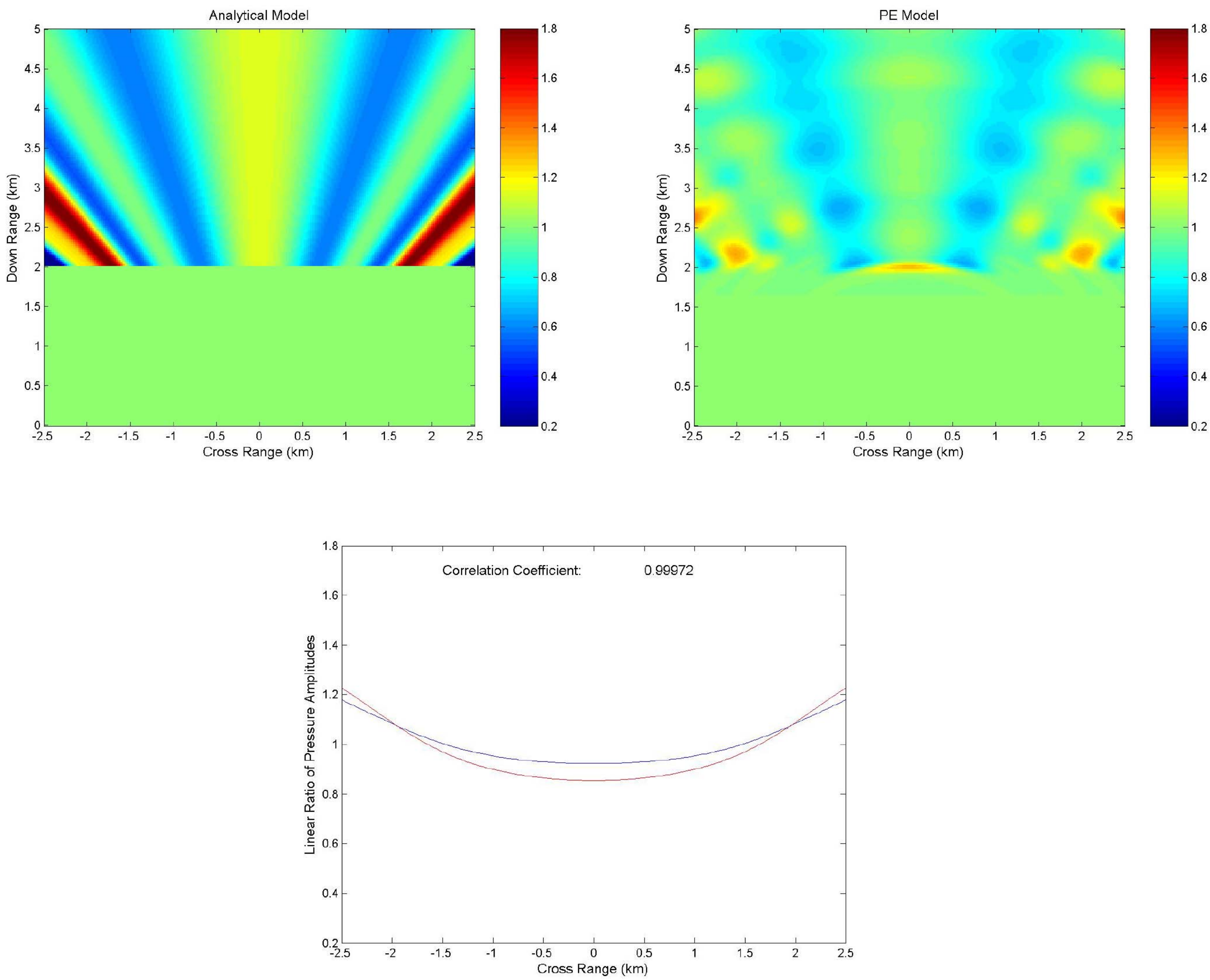

Figure 1: Comparison of ratio of modal energies between single-scattering model solution (upper left figure, red curve below) and 3-D MMPE solution (upper right figure, blue curve below) for mode 5 at 150 Hz. Lower figure shows comparison at 5 km range.

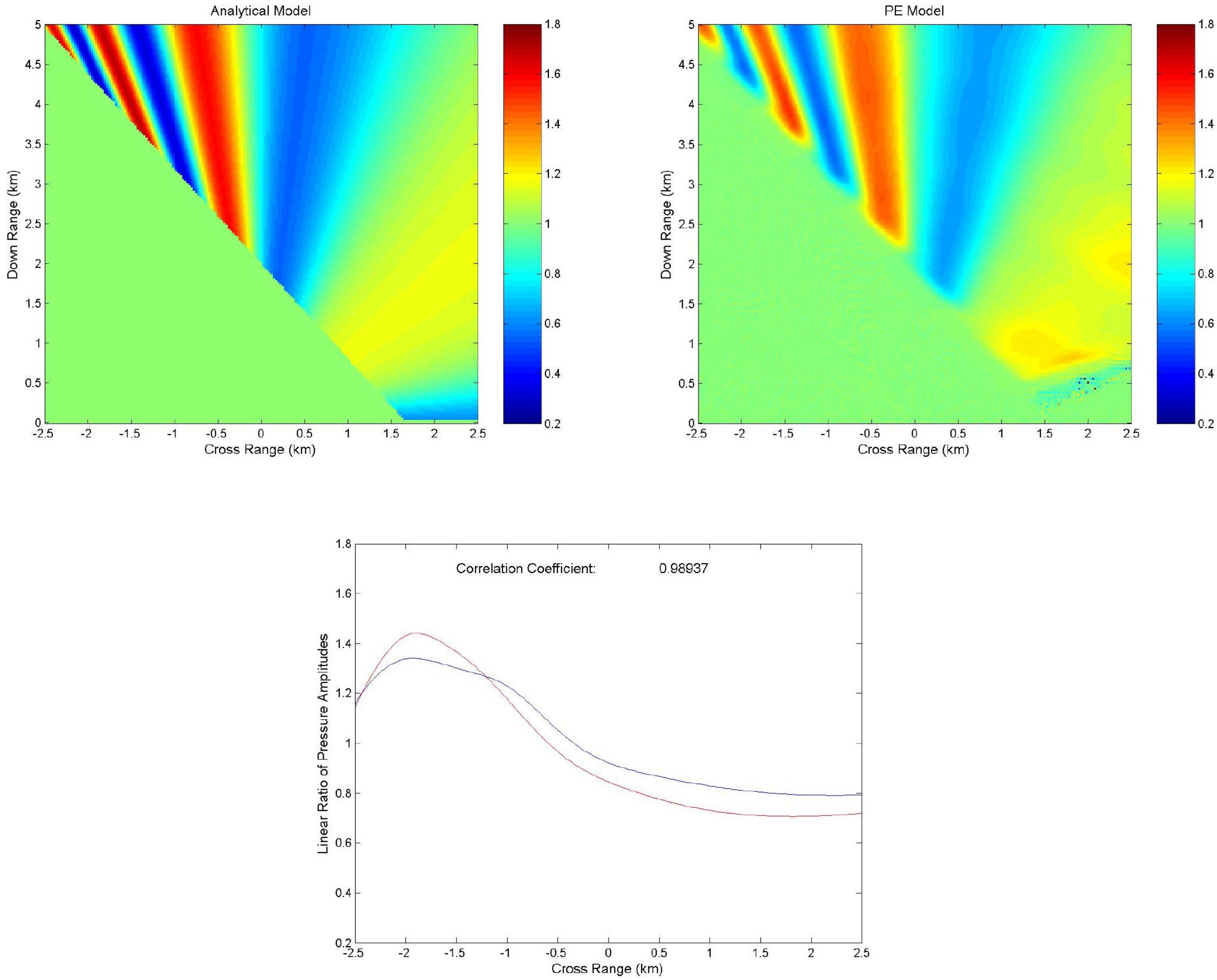

Figure 2: Comparison of ratio of modal energies between single-scattering model solution (upper left figure, red curve below) and 3-D MMPE solution (upper right figure, blue curve below) for mode 1 at 150 Hz. Lower figure shows comparison at 5 km range.

Table 1. Correlation Coefficients for RMEs at 5 km for varying NLIW angles.

NLIW Angle	Correlation Coefficient			
	Mode 1	Mode 2	Mode 4	Mode 5
0	0.9997	0.9757	0.9347	0.8165
10	0.9810	0.9810	0.9046	0.9128
20	0.9894	0.9831	0.8183	0.8850
30	0.9715	0.9652	0.8712	0.8294
40	0.9509	0.9647	0.8684	0.8107
50	0.8758	0.9281	0.8155	0.7499
60	0.8191	0.9103	0.8187	0.8417
70	0.8552	0.9331	0.7985	0.8262
80	0.8438	0.8028	0.2828	0.7671

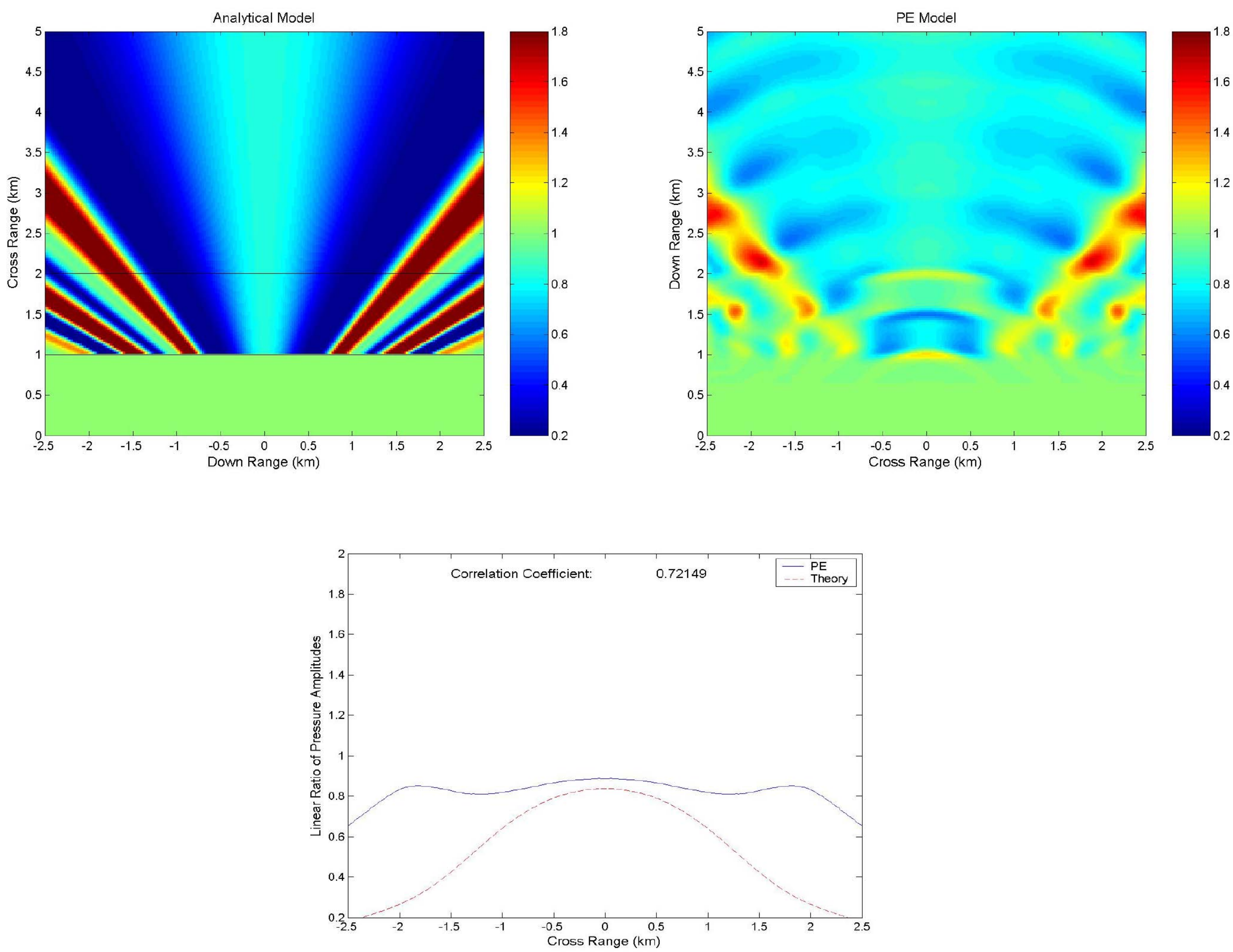

Figure 3: Comparison of ratio of modal energies between single-scattering model solution (upper left figure, red curve below) and 3-D MMPE solution (upper right figure, blue curve below) for mode 5 at 150 Hz. Lower figure shows comparison at 5 km range.

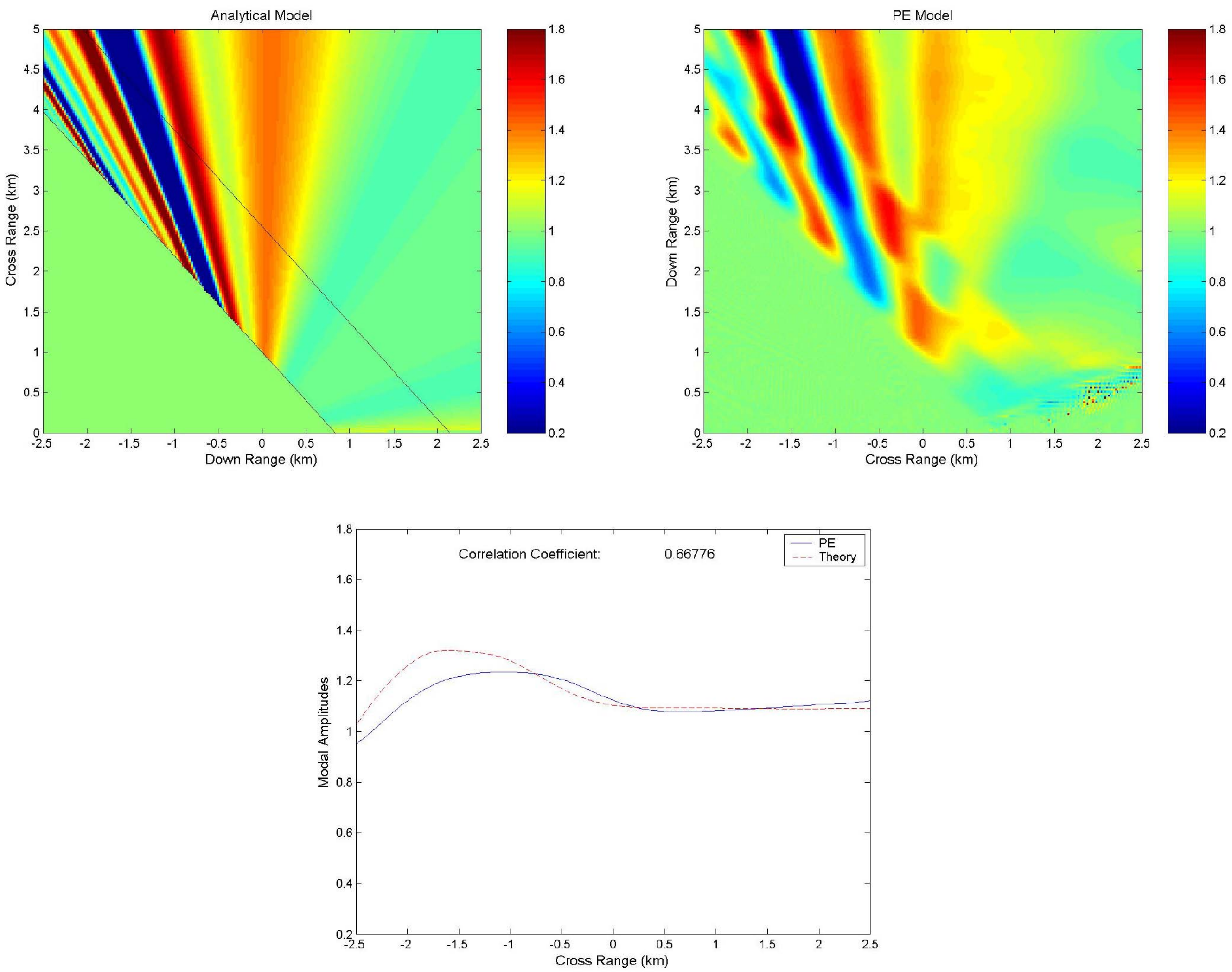

Figure 4: Comparison of ratio of modal energies between single-scattering model solution (upper left figure, red curve below) and 3-D MMPE solution (upper right figure, blue curve below) for mode 1 at 150 Hz. Lower figure shows comparison at 5 km range.

Table 2. Correlation Coefficients for RMEs at 5 km for varying NLIW packet angles.

NLIW Packet Angle	Correlation Coefficient			
	Mode 1	Mode 2	Mode 4	Mode 5
0	0.9881	0.8861	0.7838	0.7215
10	0.8796	0.9230	0.4275	0.9666
20	0.6678	0.7524	0.7295	0.9214
30	0.7897	0.3533	0.6867	0.8111
40	0.8318	0.4524	0.4485	0.6482
50	0.4876	0.6988	0.5664	0.6794
60	0.4887	0.6765	0.6342	0.9375
70	0.6025	0.5699	0.4101	0.9366
80	0.5497	0.7476	0.2828	0.9058

Geo-acoustic Inversion Studies:

The data reduction and noise analysis for the short time duration waveforms transmitted into the sea bed during SAX-04 were also completed.[10] It was found that the source levels at the lowest frequencies were not sufficient to overcome the noise floor of the data acquisition system on the acceleration channels due to the relatively low sensitivity of the acoustic accelerometers. While loss of data at the low end of the band is undesirable, it was also found that the usable bandwidth of the source was greater than expected at higher frequencies. Thus, the complex impedance was characterized with good frequency resolution across two octaves centered at 1.2 kHz. Figure 5 illustrates the specific acoustic impedance computed for one suspended and one buried sensor.

Development of refinements to account for the non-neutral buoyancy of the buried sensors is the current focus. The basic approach has been improved to include the change in acoustic accelerometer sensitivity that results from the positively buoyant buried sensors in a bottom without shear. Implementation of this refinement is currently underway.

Work to investigate a second potential inversion method was begun during the summer of 2009. Frisk and Lynch[6] developed a method to characterize the shallow water wave guide by Hankel transformation of the pressure amplitude and phase versus range for a continuous wave signal. It is planned to extend this approach to acoustic data that include the vector field, such as intensity.

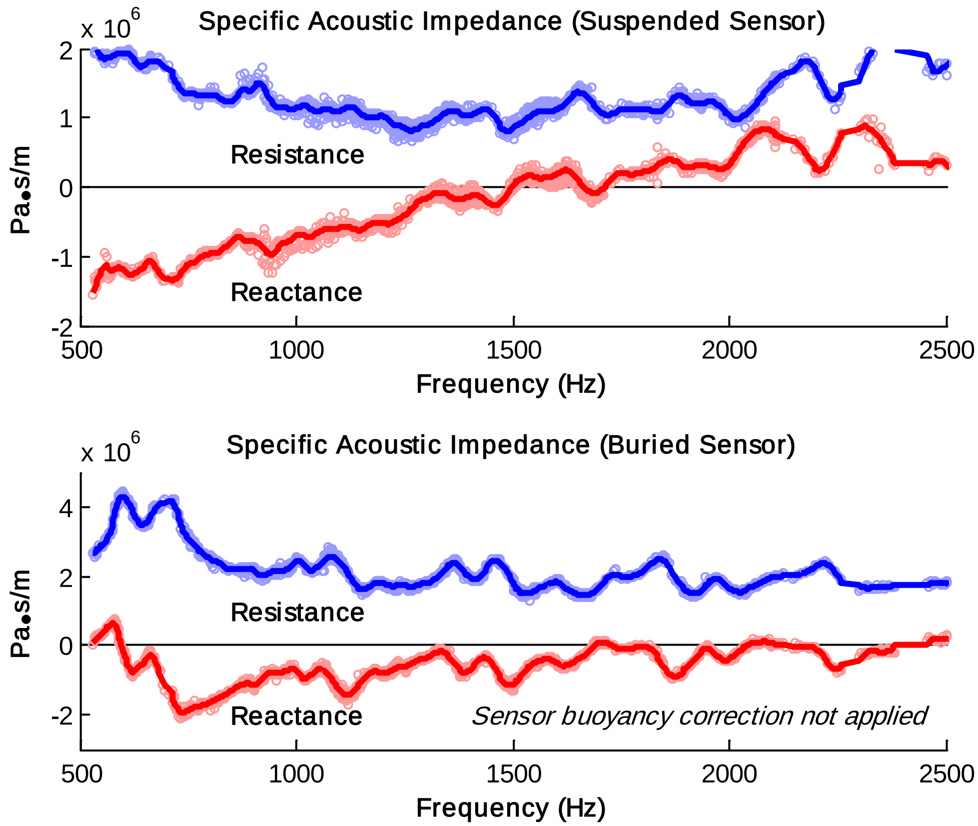

Figure 5: SAX-04 impedance data (normal incidence).

To support validation of the proposed inversion method, an experiment was conducted in Block Island Sound in conjunction with acoustic transmission loss measurements performed by the State of Rhode Island. The measurements were conducted as part of Rhode Island's ocean special area management plan (SAMP) associated with the construction of an offshore wind project in state waters. A short vertical receiving array (and data acquisition system) consisting of two USRD H52 hydrophones and one Wilcoxon-Research TV-001 acoustic vector sensor was built. The array was deployed vertically from a small sailing vessel to minimize the potential for acoustic interference from propulsion and auxiliary engines. The experiment was conducted in approximately 100 feet of water while a continuous wave acoustic source (operated by the State of Rhode Island) was towed over the longitudinal axis of a submerged glacial lake bed located to the northwest of Block Island as shown in Figure 6.

Figure 6: Hybrid vertical array and target geoacoustic feature.

The experiment successfully collected acoustic data, including particle acceleration measurements, for source-receiver separations ranging from about 20 meters to 5 kilometers. This data set will support continued investigation of vector based inversion methods in FY 2010.

IMPACT/APPLICATIONS

The shallow-water environment poses many obstacles to submerged and surface operations. Not the least of them are the obstacles posed to acoustic detection of quiet contacts. The presence of Non-Linear Internal Waves (NLIWs) within this environment induce acoustic variability and phase fluctuations which limit signal processing capability and further complicate operations in this environment. However, a better understanding of how NLIWs affect sound propagation may lead us to take advantage of some of these effects, such as how NLIWs focus acoustic energy into certain modes allowing detection of quiet sources above background noise. An understanding of the phase fluctuation may also lead to better processing algorithms. While multiple numerical simulations have been conducted which allow for the effects of NLIWs to be intuited from them, an analytical model which can predict the effects on acoustic propagation by the physical parameters of the NLIWs had not been produced until the development of a single scattering analytical model of those effects by Prof Colosi (NPS).

Information contained in the acoustic vector field is being used to develop new inverse methods for estimation of sea bed geoacoustic properties. Significant progress has been made toward the development of a method to invert the observed specific acoustic impedance for geoacoustic properties of the sea bed. The data requirements are not particularly demanding as relatively little information about the source is required. Additionally, the data is collected at the location for which the parameters are being estimated, vice being collected with a multi-static system operating over significant source-receiver separations. Thus, it may ultimately prove feasible to autonomously collect the data needed to support impedance based inversion from a submerged vehicle with little or no supporting surface expression.

RELATED PROJECTS

On-going work studying the 3-D effects of NLIWs is being conducted by Prof John Colosi of the Naval Postgraduate School. In addition, the 3-D MMPE model for computing these effects is now being utilized by Prof Jim Miller and his students (Univ of Rhode Island), as well as Prof Mohsen Badiey and his students (Univ of Delaware).

New inversion algorithms that incorporate vector field information are also being investigated against vector field predictions using the 2-D MMPE model by Prof Jean-Pierre Hermand at the Université libre de Bruxelles, supported under an ONR-G NICOP.

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HONORS/AWARDS/PRIZES

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